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ABSTRACT

The pamphlet reviews cognitive and developmental psychology research in which skilled and less skilled performance patterns and mechanisms have been compared. Knowledge has been described, in theory, in terms of an associative network in which concepts are represented as the nodes of the net, and relations between concepts serve as associative links. Variations in knowledge may be described in terms of amount, organization, and accessibility. Competent performance is often indexed by the ability to retrieve information easily. The initial representation that one constructs during a task is an important determinant of performance characteristics. Individuals with outstanding abilities develop representational competence that leads to high-quality performance and to abilities that enable them to predict, derive questions, and quickly get to main points. Increased automaticity in cognitive processing provides easy accessibility to relevant knowledge and frees up attentional resources which can then be directed toward other aspects of the task. Research needs to be conducted on the differences between gifted and average individuals in the acquisition of knowledge and related cognitive skills, in the accessibility of information, in the representation of problem situations, and on how such differences determine the properties of outstanding performance. (JW)

LEARNING RESEARCH AND DEVELOPMENT CENTER

COGNITIVE STRUCTURE AND PROCESS IN HIGHLY COMPETENT PERFORMANCE

1986/15

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University of Pittsburgh

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3. Cognitive Structure and Process in Highly Competent Performance

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The study of the gifted is a relatively uncharted area of cognitive psychology. Although there is a fairly long history of research investigating the nature of intelligence and superior intellect, there have been few attempts by cognitive psychologists to understand the processing characteristics of people at the upper end of the intelligence/performance continuum. In general educational practice, certain people are considered gifted because they exhibit extremely skilled or competent performance. This is illustrated by the several definitions of giftedness in the first two chapters of this volume, including that of former U.S. Commissioner of Education Sidney P. Marland, who described gifted and talented children as exhibiting "high performance" and "demonstrated achievement" (Marland, 1972).

In this chapter, consistent with this orientation, we ask the question: What allows people to perform in highly competent ways and to exhibit

the very skilled performance that is apparent in highly gifted people? From a psychometric point of view, this ability is often attributed to a high level of general intelligence (g) as indexed by high scores on tests of mental abilities or by assessments of various factors of intelligence. Recent attempts to understand the cognitive mechanisms involved utilize an information-processing approach that characterizes factors of intelligence and aptitude in terms of component processes. Variations in intelligence and aptitude test performance have been related to variations in speed of processing (Hunt, 1976, 1978; Keating & Bobbitt, 1978; Vernon, 1983), to variations in problem representation and "insight" skills (Sternberg & Davidson, 1983), to differences in accessible knowledge (Pellegrino & Glaser, 1982), and to variations in the flexible use of strategies (Campione, Brown, & Ferrara, 1982). There has also been considerable discussion of variations in metacognitive skills such as planning, questioning, and solution monitoring (Brown, 1978; Sternberg, 1981). In general, research indicates that people who exhibit highly competent performance have easy and fast access to relevant information, are able to view problem situations in qualitatively distinct ways, can use strategies effectively and flexibly, and have better metacognitive skills.

To help us better understand the performance of the gifted and delimit the importance factors that characterize competent performance, in this chapter we review research in cognitive and developmental psychology in which skilled performance has been compared to less skilled performance. In much of the research comparing children with learning problems to more typical children, young children to older children or adults, and novices to experts, researchers have taken this approach. These comparative studies have shown that an important determinant of skilled performance, related to the components of competence just listed, is the knowledge that people bring to a task. That available organized knowledge exerts a considerable influence on performance characteristics is no longer debated within cognitive and developmental psychology. For example, recent research on developmental differences in memory performance emphasizes the role of knowledge (Chi, in press). Developmental differences in memory performance are dramatically reduced when the familiarity of the materials to be learned is taken into account (Bjorklund & Zeman, 1982; Richman, Nida, & Pittman, 1976). These differences can even be reversed when the younger group is more familiar with the stimulus materials than is the older population (Chi, 1978; Lindberg, 1980).

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In a similar vein, research in which experts and novices are compared in domains such as baseball (Chiesi, Spilich, & Voss, 1979), bridge (Charness, 1979), chess (de Groot, 1965; Chase & Simon, 1973), physics (Chi, Feltovich, & Glaser, 1981; Simon & Simon, 1978), and medical diagnosis (Lesgold, 1984), to name just a few, clearly shows that domain-specific knowledge has significant influence on cognitive skills. In addition, there has been a growing shift in emphasis within various computer simulations of cognitive performance from specifying general procedures or strategies to describing the underlying knowledge structure in a given domain (Anderson, 1983a; Chi, Glaser, & Rees, 1982; Minsky & Papert, 1974).

In this review, our intention is not to present this discussion so that future theorists will list knowledge as yet another separate factor that needs to be considered in the discussion of the gifted. Rather, we review theories and experimental findings from cognitive and developmental psychology that suggest that the operation of a well-organized knowledge base provides a framework in which to discuss and understand the various components of highly competent behavior and the interrelationships among them.

Knowledge as an Associative Network

Prior to discussing the consequences of possessing a well-organized knowledge base for performance, we need to expand upon what we mean by knowledge and some aspects of its architecture. One way in which knowledge has been theoretically described is in terms of an associative network (Anderson & Bower, 1973; Collins & Quillian, 1969; Norman & Rumelhart, 1975). Within an associative network, concepts are represented as the nodes of the net, whereas relations between concepts serve as associative links. Three of the properties of associative links are as follows. They specify the relation among concepts, such as "belongs to the category of," or "has a certain property." Associative links can vary in strength—some concepts are strongly associated with each other, whereas others are only weakly associated. Associative links can be either excitatory or inhibitory.

This associative network is conceptualized to operate on the basis of the "automatic" spread of activation along associative links (Anderson, 1983b; Collins & Loftus, 1975). Spread of activation operates such that when a word is encountered, the concept in memory corresponding to it is excited. When a node receives excitation, its level of activation rises, eventually reaching a threshold point, at which time activation spreads to related concepts. This spread of activation to related concepts is termed *secondary activation*. The amount of secondary activation gen-

erated depends upon the level of activation of the originally activated node and the strength of the associative links between concepts. A node spreads activation in proportion to its level of activation, and stronger associations lead to stronger secondary activations. Excitatory links increase the level of activation of a related node, whereas inhibitory links decrease the level of activation of associated nodes.

A consideration of how such an associative network might vary among individuals must include at least three aspects. First, there are issues of quantity, that is, the number of specific concepts available to a person. An expert in a given domain is thought to have a greater amount of declarative knowledge (knowledge of concepts and facts) about that domain than does a novice. Similarly, an adult might be considered to have more conceptual knowledge than a young child. Similar comparisons can be made about metaknowledge—knowledge of one's own processing capabilities and regulation of processing. In this architecture, then, knowledge might be indexed theoretically by estimating the number of nodes within memory.

Second, at a different level, are issues of organization, that is, how one piece of information relates to another. Developmental issues of organization have emphasized a shift from a thematic organization, in which things go together because they occur together in space or time, to a taxonomic organization, in which things go together because they belong to the same conceptual categories (see Mandler, 1983, for a review of this literature). Similarly, experts in a field might organize information according to different conceptual categories than do novices (Chi et al., 1981). This knowledge might be indexed within a semantic net through variations in the associative links that connect pieces of information.

The postulated differences within node-link structures for individuals at different levels of competence are illustrated in Figures 1 and 2 (Chi, Glaser, & Rees, 1982). Two kinds of subjects, experts and novices in physics, were asked to tell all they could about a physics problem involving an inclined plane. The subjects categorized the problem according to how they would solve it. The experimenters translated the subjects' protocols into node-link networks and compared the structures of experts and novices.

Inspection of these two figures reveals interesting differences in both the content and organization of these representations. For the novice (Figure 1), the representation consists primarily of surface features, such as the presence of a plane, the angle at which the plane is inclined with respect to the horizontal, the height and mass of the block, and whether or not it has friction. For the expert (Figure 2), the structure is related to and organized around basic laws of physics, such as principles of mechanics, conservation of energy, and Newton's laws of force. At the lowest level of the representation are the structural, or surface features of the problem. The novice represented at least as many surface features of the

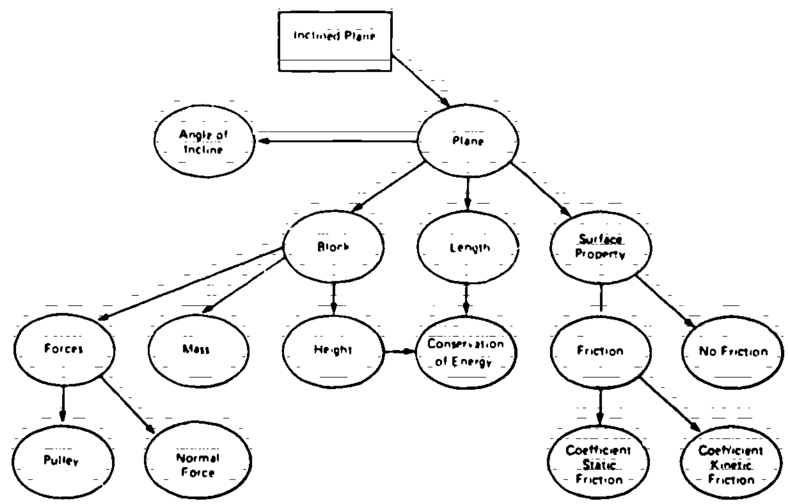

Figure 1. Network representation of a novice's schema of an inclined plane. Reprinted from Chi, Glaser, and Rees (1982) by permission.

problem as did the expert. For the novice, however, these features are not subordinate to basic physics principles but, in fact, appear to be more salient than the principles that are so important to the expert. In addition, the expert's knowledge includes not only principles but also an understanding of the conditions of their use (see dotted-line enclosures). The novice's knowledge fails to include these conditions.

Associative networks can also differ according to the accessibility of information, that is, how easy it is to retrieve a concept or a relation. Thus, a concept might be available, in that there is a node representing that concept in memory, but be relatively inaccessible, in that it receives very little activation from related concepts. Theoretically, one can say whether knowledge of a given concept is available or not: Is there a node representing this concept in the knowledge base? Is there an associative link connecting these two concepts? However, available knowledge might be differentially accessible. Whereas it might require quite a bit of effort to access one piece of available knowledge, other information might become accessible with little or no effort being made. In this chapter, we will conceive of differences in accessibility as being related to variations in the strength of the associative links.

These three ways of describing variations in knowledge—amount, organization, and accessibility—are obviously interrelated. In fact, it is probably impossible to consider one without also taking account of the

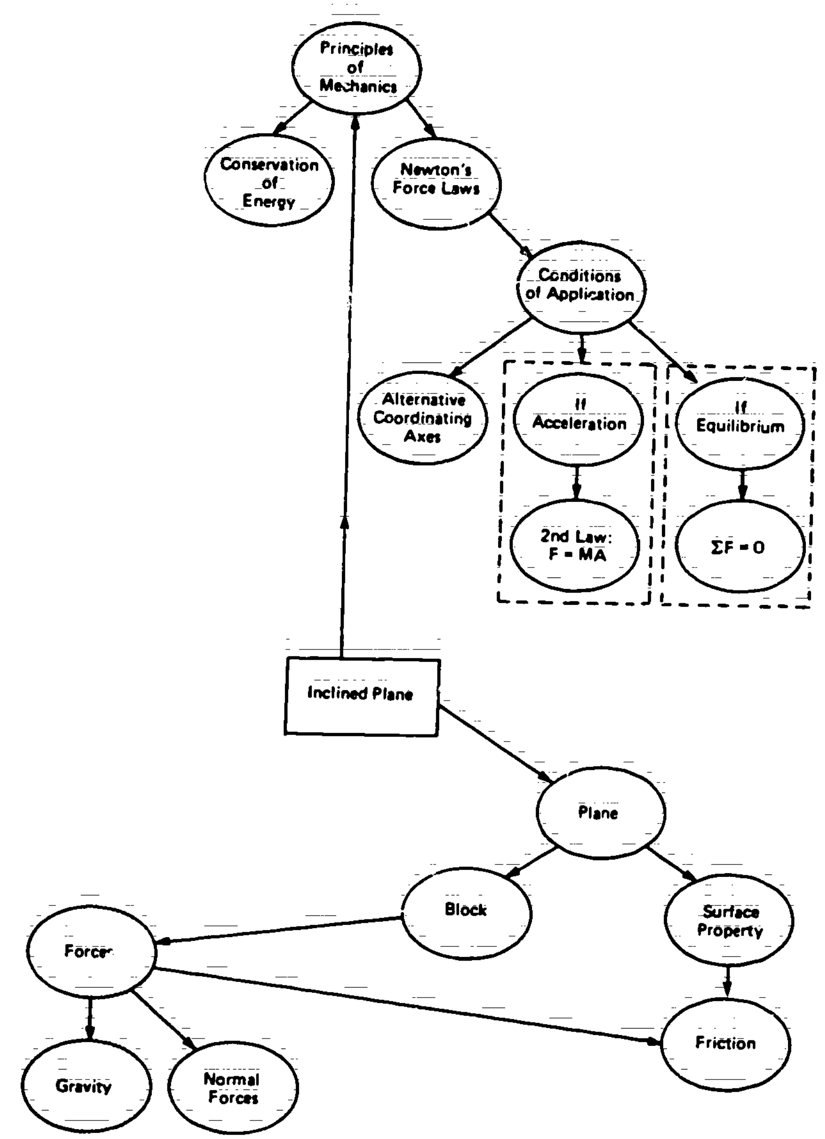

Figure 2 Network representation of an expert's schema of an inclined plane. Reprinted Chi, Glaser, and Rees (1982) by permission.

others. With this interrelationship in mind, we will discuss the consequences of having a well-organized knowledge base. Our particular emphasis is on the consequences of variations in accessibility of knowledge as a significant feature of cognitive skill and gifted performance.

The Retrievability of Knowledge

In some situations people seem to have ready access to information, and in other situations people need to work in a controlled way at deriving such information. There are also large individual and developmental differences in people's ability to access information, and competent performance is often indexed by the ability to retrieve information easily. People who exhibit expertise within a domain of knowledge are able to access information rapidly. Furthermore, Keating and Bobbitt (1978) found that children of above-average ability search memory more rapidly than do those of average ability. An important question is how the ability to quickly access information develops. What are the factors that determine when information is rapidly retrieved and when it must be derived more slowly?

For most tasks there is more than one way to obtain information. There are a variety of problems for which we all seem to have the ability to arrive at an answer in an automatic manner. To take two very simple examples, when asked their name or current address, most people have answers available almost immediately. There is little sense of doing anything special to obtain the answer; the information is automatically accessible. As a matter of fact, there is probably no way one can prevent answers to such questions from coming briefly into awareness.

On other problems, there seems to be a need to run through some procedure in order to derive the answer. Take the question, "How many windows are there in the place where you are currently living?" Most people probably do not have this information encoded in such a way that it can be readily retrieved. A person can derive this information, however, by picturing him- or herself walking through the house counting the number of windows. This procedure requires a person's attention in order to be carried out and can be started or stopped at any point prior to obtaining the answer.

One important aspect of the development of competent performance is a shift from the reliance on conscious controlled processing to derive an answer to the automatic and fast access of an answer. Controlled processing is generally characterized as a slow, primarily serial, effortful, capacity-limited, subject-controlled process. Alternatively, automatic processing is a fast, parallel, fairly effortless process that is not limited by

processing capacity constraints and is not under direct conscious control (Neely, 1976; 1977; Schneider & Shiffrin, 1977).

One perception of competence is derived from observing the procedures people use. For example, given the problem 7 + 2, you might access a store of facts and retrieve the answer 9. Alternately, you can generate the answer by first counting to 7, then counting two more and observing the end result. Adults and older children are able simply to retrieve the answer 9 in an automatic fashion, with no awareness as to how the answer is generated; they simply know that 7 + 2 equals 9. Children beginning elementary school, however, have to generate most answers by using one of a variety of procedures. From this point of view, most people would judge the adult or older child to be more proficient in arithmetic computation than is the younger child, even though the younger child may be proficient in generating a procedure to produce the answer.

Simple addition is a good task with which to investigate the development of competence. The methods by which people perform addition show a clear developmental progression from using procedures (such as counting) for generating answers (Ashcraft, 1982; Groen & Parkman, 1972; Resnick, 1982; Siegler & Robinson, 1982) to having the ability to access the information easily. Recent research on young children's addition performance has emphasized the derivative nature of children's processing. Groen and Parkman (1972) found that the smallest number within an addition problem was the best predictor of solution times for the children. On this basis, they set forth a *min* model, proposing that children add by selecting the larger of two addends and counting up from it the number of times indicated by the smaller addend. Similarly, Ginsburg (1977) found that children often alluded to counting-on from the larger number when verbalizing about the solution process. Resnick (1982) illustrated other procedures that children use to generate answers to addition problems. For example, given the problem 3 + 4, a child might change the problem to 3 + 3, access the answer, and then add 1 to it. Each of these examples shows that children must derive answers to addition problems in a controlled way.

Adults, however, appear to perform simple addition by simply retrieving the answers (Ashcraft, 1982; Ashcraft & Battaglia, 1978; Groen & Parkman, 1972). For example, in order for Groen and Parkman's data on adults to fit the min model, the incrementing process used by adults would need to be faster than any other known elementary process. On the basis of their results, they postulated that adults retrieve the answer 95 percent of the time and use the min process only 5 percent of the time. Thus, on this task there is a developmental progression of competence from having to derive the answer to simply retrieving the information.

Within this developmental trend away from the use of strategies to derive answers, Siegler and Robinson (1982) observed, in viewing videotapes of four- and five-year-old children working on addition problems,

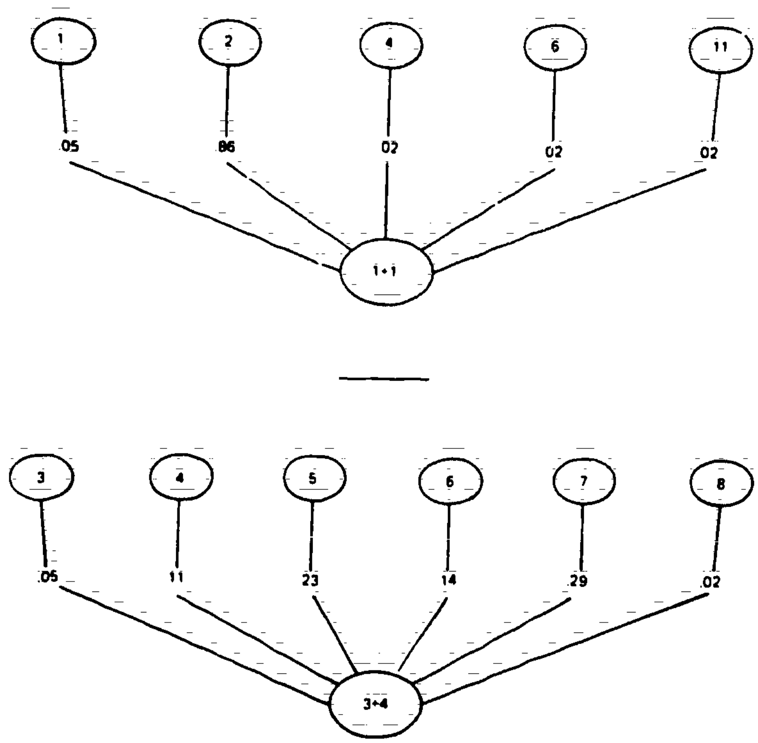

Figure 3. Distribution of associations for problems $1+1$ and $3+4$.

that competence varied from problem to problem. Children overtly used strategies to solve many of the problems, but sometimes they were able simply to retrieve the answer. On retrieval trials, there was no visible or audible intervening behavior and their solution times were faster. To account for this difference, Siegler and Robinson assumed that the representation of addition knowledge consists of associations of varying strengths between each problem and possible answers. From normative data, they were able to estimate the associative weights. Figure 3 shows the resulting distribution for two problems, $1+1$ and $3+4$. The distribution of responses from the problem $1+1$ to possible answers is peaked toward the answer 2. Peaked distributions are those in which the strength of the associative links from the problem to possible answers is much greater for one answer than for other answers. On problem $3+4$, the distribution of the associative weights from problem to possible answers was more even.

Children tended to access the answer (rather than deriving the answer) on problems for which there was a peaked distribution of associa-

tions. Furthermore, as the peakedness of the distribution increased, solution times on retrieval trials decreased. On problems for which the strength of the associative links between the problem and answers was more evenly distributed over a variety of answers, children tended to use a procedure to derive the answer. Using such data, Siegler and Shrager (1984) proposed a learning model by which gradually increasing the peakedness of the distributions from addition problems to answers predicted behavior much more similar to that of adults. Within this model, then, learning is assumed to be the strengthening and weakening of associative weights between pieces of information.

The ability to access information easily also affects competence on more complex forms of problem solving. We have suggested that an important component of competent and skilled behavior is the ability to have easy and rapid access to information. One way to think about the issue of accessibility is in relation to the automatic spread of activation along associative pathways in a knowledge structure. If the associative links are weak and few, then the rise in the level of activation of related knowledge will be negligible, and the information should still be relatively inaccessible. In such cases, a person would need to use a procedure to derive information. The greater the amount of excitation a node is receiving, either through stronger or a greater number of inputs, the higher the level of activation will be and thus the more accessible the information becomes. Accessibility, then, can be viewed along a continuum. Weak associative links provide little input to allow information to become automatically accessible. As the spread of activation increases, due to stronger associative links, related information becomes more accessible. To the extent, then, that giftedness is indexed by rapid access to relevant knowledge, gifted people might be characterized as having knowledge with strong associative links connecting related pieces of information. Future research needs to focus on how such knowledge is acquired. This issue is raised again in the last section of this chapter.

Accessibility, Representation, and Problem Solving

Variability in access to relevant information also influences competence in complex forms of problem solving. Consider the following example:

> A block of mass M1 is put on top of mass M2. In order to cause the top block to slip on the bottom one, a horizontal force F1 must be applied to the top block. Assume a frictionless table. Find the maximum force F2 which can be applied to the lower block so that both blocks will move together.

Experts and novices show substantial qualitative differences in the cognitive structures and processes that compose their ability to solve such problems. With problems of this kind, a person must first understand what the problem entails—what the important concepts presented in the problem are and how they are related. In this initial encoding, a person builds a cognitive representation or mental model of the problem. Some of the information used to construct this representation is explicitly stated in the problem statement; other information is inferred. Understanding and insight into the problem comes from the interaction between the information explicitly stated in the problem and a perso. prior experiences and knowledge. Variations in the accessibility of relevant information affect the structure and content of the person's initial understanding or mental representation of the problem. The quality of this representation, in turn, has a large impact on determining the efficiency, elegance, and precision of subsequent processing needed for solving the problem (Gentner & Gentner, 1983; Greeno & Simon, in press; Johnson-Laird, 1982, 1983; Larkin, in press).

Finding the Problem

Problem representations are created very rapidly upon presentation of a problem. For example, Hinsley, Hayes, and Simon (1978) found that when college students were asked to categorize algebra word problems into types, they did so very quickly—sometimes after reading just the first phrase of the problem statement. Similarly, Chi et al. (1981) found that experts and novices in physics both were able to categorize physics problems very quickly, although the specific content of the categories differed markedly.

There is much evidence to suggest that variations in the problem representations that are constructed occur because of differences in the ability to perceive the relationships among materials rather than through variations in the strategies with which people approach or solve the task. The now classic studies of de Groot (1965) and Chase and Simon (1973) showed that players at different levels of chess skill were essentially alike in the number of moves they considered, in the depth of their search for move sequences, and in similar measures obtained from spoken protocols, but that substantial differences occurred in their perception of the problem configurations. The chess master is thus seen as a superior problem recognizer rather than a deep thinker, and this theoretical position accounts for some of the extremely competent performance of expert chess players. "It explains how a chess master is able to defeat dozens of weaker players in simultaneous play: because for the most part he simply relies on his pattern recognition abilities—his so called "chess intuition"—to generate potentially good moves" (Chase & Chi, 1981, p. 115).

Thus, as a person gains increased knowledge and familiarity within a domain, his or her representation or understanding of problems changes. As already indicated, in the study of physics problem solving, Chi et al. (1981) found that experts and novices began their problem representations with specifiably different problem categories. When asked to classify problems on the basis of how they would solve them, novices tended to sort physics problems on the basis of surface characteristics of the problem: similar objects (such as a spring or an inclined plane), key words (such as mass or friction), or the interaction of several object components (such as a block on an inclined plane) as depicted in Figure 1. In addition, the novices' verbal explanations of their categories emphasized these structural characteristics. By contrast, experts tended to classify the problems according to major physics principles (or fundamental laws) governing the solution of each problem, as illustrated in Figure 2. The verbal protocols of experts also confirm the basis of these groupings. In a similar vein, Egan and Schwartz (1979) found differences between experts and novices in electronics in the way they reconstructed symbolic drawings of circuit diagrams. Skilled technicians utilized the functional nature of the elements in the circuit, such as amplifiers, rectifiers, and filters, whereas novice technicians produced chunks based more upon the spatial proximity of the elements.

A major difference between experts and novices in these studies is that the representations of the novice are based primarily on information that is explicitly presented in the problem statement—objects, key words, visual proximity. Experts, however, are able to base their representations on higher-level principles—information that is not explicitly stated within the problem. They can quickly retrieve from memory functional or principled relations among the concepts. This ability of the expert can be attributed to the existence and accessibility of structures of prototypical knowledge or problem schemata that unify superficially disparate problems. In line with general schemata theory (Rumelhart, 1981), these schemata provide information structures that can be rapidly accessed to make apparent the inferences needed concerning the relations in the information presented in the problem.

Choosing a Strategy

On the basis of different mental representations of problems and differential accessibility to information, people can use markedly different strategies to work on a problem. Again, clear examples are offered within the context of expert–novice differences in physics problem solving (Larkin, McDermott, Simon, & Simon, 1980; Simon & Simon, 1978). Some of these differences are evidenced in quantitative measures of problem solving. Simon and Simon (1978) noticed a 4 to 1 difference between their experts and novices in the speed with which problems were solved. Also,

Larkin (1979) has claimed that experts were able to retrieve a number of physics equations in successive chunks with very small interresponse intervals followed by a longer pause. The novices did not exhibit this pattern of pause times in equation retrieval

The most substantial differences between experts and novices are evidenced in the qualitative ways in which they appear to solve problems. While working on physics problems, the expert appears to use a "working forward" strategy, whereas the novice uses a "working backward" strategy. The expert works from the variables given in the problem using the fundamental principles relevant to the problem to suggest which equations should be used. The expert can then successively generate and solve equations from the given information. The novice, on the other hand, starts with an equation containing the unknown of the problem. If it contains a variable that is not among the givens, then the novice selects another equation to solve for it, and so on, using essentially a general means-ends strategy (Newell & Simon, 1972) by which each equation is compared with the desired final state of the problem. The novice then reduces deviations from this desired final state by generating equations to solve for new unknowns. The initial mental representation strongly influences the choice of strategy that is used. When the problem becomes difficult, experts switch from the forward working strategy to a sophisticated means-end analysis, and this occurs, it appears, when they cannot construct an elaborate representation for such problems (Larkin, 1977).

The nature of one's mental representation of a problem has also been shown to affect the ability to use such problem-solving skills as questioning, predicting outcomes, and deriving the main points. Such skills are applicable to a variety of domains, and skilled thinkers have been shown to use them in solving problems, whereas less skilled thinkers do not (Brown, 1978; Sternberg, 1981, 1984). Miyake and Norman (1979) have shown that the ability to spontaneously ask questions about a body of knowledge depends upon one's existing knowledge of the material. They asked people who had different amounts of expertise in computer text editing to work on two editing tasks. People who exhibited high competence and had considerable experience with computer test editing asked more questions about the task when the editing task was difficult. Novices, however, asked many more questions with the easy task. There were no differences between the two groups in the number of questions asked about a baseline task where there were no knowledge differences. Thus, the tendency to spontaneously ask questions regarding the editing task was dependent upon the level of knowledge they possessed when they came to the task. The novice exposed to expert level material does not have a problem representation that is detailed enough to suggest what sorts of questions should be asked and therefore cannot obtain needed information. Asking a question implies a proper structure of knowledge with which to formulate the question. It is on difficult tasks that com-

petent people seem to ask the most questions, suggesting that they have more elaborate, better defined representations of situations.

The ability to predict outcomes or to supply additional information has also been shown to vary with knowledge. Larkin (in press) presented an expert and a novice with problems in reduced forms, in which only the key terms of the problems, such as objects (e.g., blocks, planes, ropes), attributes (e.g., velocity, height), and values were presented. The task was to predict what the original problem statement was. The expert was much better at this task than the novice and was able to construct the problems so that solving the constructed problem was equivalent to solving the original problem. In most cases the novice was unable to derive these problems.

Similarly, Chiesi et al. (1979) tested people for knowledge of the game of baseball. They identified a group of subjects (high-knowledge) who knew quite a bit about the strategies of the game, and a second group (low-knowledge) who knew the basic rules of the game and a bit about which professional teams were currently doing well, but little about the game's finer points. Subjects were asked to write down all the possible outcomes they could think of for specific baseball situations. High-knowledge individuals knew more possible outcomes and could better specify which ones were likely to occur. More important, however, than the number of outcomes people were able to predict was that high-knowledge individuals were more likely to produce basic action sequences involving strategic, goal-oriented plays. Thus, in both of these examples, the ability to predict appeared to be dependent upon the ability to access an elaborated representation of the domain.

Even skills that lead to extraordinary memory performance have been shown to be knowledge dependent. Recent research conducted by Chase and his associates has supported this view (Chase & Ericsson, 1981; Ericsson, Chase, & Faloon, 1980). A student, SF, who had average memory abilities and average intelligence for a college student, spent a year and a half engaged in long-term practice on a memory-span task. Over this time, SF was able to increase his memory span from 7 to 79 digits. (Memory span for most people is approximately 7.) The protocols obtained by the experimenters indicated that during this extensive practice, SF, a good long-distance runner, devised the strategy of recoding digits into running times. For example, SF recoded 3492 as "3:49.2—near world-record time for the mile," which for him was a single chunk. Since SF had many running times stored in memory, he could easily chunk most cases of four digits. In those cases in which he could not, SF recoded the four digits into a familiar date or age. In addition, SF had numerous categories of running times, ranging from half-mile times to marathon times, and many subcategories within each category, for example, near world-record time, very poor mile time, average mile time for the marathon, and average work-out mile time. By organizing the running times

hierarchically, SF was able to exhibit large memory spans for digits. However, SF's ability to memorize was limited to digits; when he was switched from digits to letters, his memory span returned to 7. In this situation, SF was not able to use his knowledge to chunk and recode the items. His knowledge of running times was thus an enabling condition for an amazing feat of memory.

In summary, competent behavior is associated with elaborate representations in which many relations not explicitly stated in a problem are rapidly accessed. The initial representation that one constructs during a task is an important determinant of performance characteristics. These initial representations are formed very quickly upon presentation of the problem, and initial variations in these representations arise because of differences in the ability to perceive automatically the relations implicit within the problem. Variations in the initial representation allow people to work on problems in qualitatively different ways and enable them to use various types of strategies. Presumably, individuals with outstanding abilities develop representational competence that leads to high-quality performance and to abilities that enable them to predict, derive questions, and quickly get to main points.

The Interactive Development of Automaticity and Controlled Processing

We have emphasized that highly competent performance seems to involve a good deal of fast and unconscious processing and the ability to perform complex operations with little apparent attention to fundamental details. It appears that rapid accessibility of information, as a function of spread of activation, allows for this ability. In addition, highly organized knowledge structures allow for a richer, more elaborate mental representation of the problem context and for the use of conscious controlled processing when required for complex cognitive effort. Many investigators have recognized the importance of the shift from controlled to automatic processing in enabling skilled performance (Lesgold, 1984; Perfetti & Lesgold, 1978; Schneider & Shiffrin, 1977; Sternberg & Wagner, 1982). This shift in processing is considered important for two primary reasons. First, it frees attentional resources that can then be used for other processing. Second, it allows for a more complex representation of a problem.

Because people have limited attentional resources for processing information, competition for these attentional resources can cause a bottleneck that limits performance capabilities. The implications of this shift in mode of processing were discussed by Schneider and Fisk (1982):

> If every processing task reduces attentional resources by a fixed, task-specific amount, then maximal performance should be a function of subject resources available and resource costs of the component tasks . . . If task resource costs are reduced with practice, then the upper bound on the number of tasks that can be combined increases with task practice. If, with practice, component tasks can be developed to the point that they require no attentional resources, then human processing capacity may have an effectively unlimited upper bound. (p. 261)

The necessity of relying on controlled processing for a substantial portion of cognitive effort imposes a limit on the amount of information with which people can work. This limiting factor might be one way to account for poor performance or, alternately, a way to consider one aspect of highly competent performance. For example, Sternberg and Wagner (1982), in reference to specific learning disabilities, suggested:

> Learning disabilities in general may result from the absence of essential basic skills, but the present authors believe that many specific learning disabilities derive from slow or limited automatization of skills. In particular, the learning disabled individual continues to have to perform in a controlled way (i.e., with conscious attention) tasks that a normally functioning individual will long ago have automatized . . . Processing resources that in others have been freed and used to master new tasks are in the disabled person devoted to tasks that others have already mastered. (p. 2)

In a discussion on reading, Perfetti and Lesgold (1978) suggested that capacity during reading comprehension is limited by momentary data-handling requirements. They proposed three components in reading that, when not fully developed, could increase the working-memory bottleneck: (a) access to long-term memory, (b) automation of decoding, and (c) efficiency of reading strategies. Having to work consciously on any one of these components diverts attentional resources that could be applied to other processing. By automatizing each of these component processes as much as possible, the reader has more resources to apply to the other components or to higher level skills, such as using context, prior knowledge, and inference to aid comprehension.

The need to rely on controlled processing, then, might inhibit competent performance. Some of the processing differences found between experts and novices can be interpreted with the constraint of limited attentional resources in mind. To return to the physics problem, for example, novices use most of their attentional resources on a working backwards strategy; their attention is invested in generating equations and solving for unknowns. Experts, however, use a working forward strategy and put less effort into generating and solving equations, thereby allowing other types of processing to occur. In fact, Simon and Simon (1978) found that experts made many more metacognitive statements than did

novices and that they commented more often on observations of errors, the physical meaning of an equation, statements of plans and intentions, and self-evaluations. It appears that automatic accessibility to relevant information helps to ease the bottleneck in attentional resources, freeing them for other processing components that increase performance competence.

Increases in automaticity also allow for a more elaborate mental representation of a situation, and the construction of such a representation enables certain processing to occur. For example, in order to improve a novice's performance, one might suggest that the novice merely needs to be taught to use the working forward strategy. Unfortunately, this approach is unlikely to succeed because the working forward strategy requires a sufficient representation of the problem so that straightforward inferences can lead to solution. A working backwards strategy, however, requires a less sophisticated representation. For a novice, at each step, there is a list of things which, if known, would result in the ability to solve the problem. Less elaborated knowledge is required to use such a strategy. Thus, an expert's representation of the problem appears to be a necessary condition for the use of the working forward strategy. This is not a problem of limited capacity; given less limited attentional resources, it is still unlikely that a novice would be able to construct the expert's problem representation. Rather, it is a matter of having easy access to the relevant knowledge needed to support the use of a given strategy.

The automatic accessibility to relevant information also enables the use of more general strategies, such as questioning and predicting. In the Chiesi et al. (1979) study, novices in baseball were less able to predict goal-oriented or strategic outcomes for a specific baseball situation. This is not necessarily a reflection of the novice's general prediction skills. Rather, in this context they were not able to construct a sufficient mental representation that would enable them to use such skills. A similar explanation could account also for Larkin's (in press) finding that novices were not able to reconstruct problems from the key words of the problem.

In this section we have emphasized the role that the development of automaticity plays in enabling skilled performance. The effects of increased automaticity are twofold. First, it provides for easy accessibility to relevant knowledge, which allows an elaborate mental representation of a problem context to be constructed. These initial mental representations have been shown to influence subsequent processing during problem solving. Second, increasing automaticity frees up attentional resources that can then be directed toward other aspects of the task. Both of these aspects, automatic accessibility to information and the reduction of the bottleneck to attentional resources, are components that depend on well-organized and highly structured knowledge. This increase in automaticity, in turn, allows for increases in skilled performance.

The Structure of Knowledge and Competent Performance

In this chapter we have suggested that certain component processes of highly competent performance can be viewed within a framework of the development of organized and cohesive knowledge structures. The ability to retrieve information rapidly, the manner in which a mental representation of a problem situation is formed, and the ability to use cognitive strategies vary with differences in knowledge. More specifically, each of these skills has been shown to vary with the relative accessibility of information. Thus, knowledge structure in specific domains appears to be an important determinant of competence. Support for these claims comes from developmental research and from comparative research on the cognitive abilities of experts and novices in various domains.

Although we have illustrated that knowledge is an important constraint on allowing competent performance, we have not addressed the issue of how that knowledge is acquired and utilized. Many researchers have shown that there are wide individual differences among people in their tendency to use general cognitive strategies or metacognitive skills for promoting skilled performance (Bransford et al., 1982; Brown, 1978; Sternberg, 1981, 1984). Even with sufficient knowledge, not all people use the skills that may be available to them. Thus, knowledge might enable, but not necessitate, the use of such skills. In fact, training in the use of such skills often noticeably improves performance (Brown, Bransford, Ferrara, & Campione, 1983; Palincsar & Brown, 1984). This approach leads to conceptions of intelligence that emphasize general skills, rather than domain-specific knowledge, and it may be that gifted people are gifted because they are more likely to use such skills to build up and use their knowledge (Sternberg, 1981, 1984; Sternberg & Davidson, 1983).

Knowledge plays a role in accounting for variability in the use of general strategies, for example, as a result of mental representations of a task. Knowledge not only enables the use of such skills, but might also affect how much effort one must apply to use them. Imagine a hypothetical situation in which question-asking behavior is observed for four people who vary in their degree of knowledge of a domain, from expert to novice, and who are presented with a problem. These four people will generate mental representations of the materials that vary in detail. Person A, an expert, studies the problem and generates a very detailed mental representation of it so that there are few gaps or inconsistencies to be filled. In this context, person A does not ask many questions. Person B has less knowledge than does person A, but is able to construct a fairly elaborate mental representation of the problem. However, in this representation, there are gaps that need to be filled. These gaps are relatively obvious from the problem representation so that with the exercise of controlled

monitoring skills, the questions that need to be asked are derived. Person C has less knowledge of the domain than does person B. Person C is able to construct a representation of the problem, but the specific information needed to suggest what questions should be asked is not immediately accessible. In such a situation, person C needs first to build up the mental representation, through controlled processing, before asking useful questions. Person D has very little knowledge of that domain and thus cannot build a meaningful representation at all. Consequently, the representation cannot suggest what types of questions should be asked, and the person does not have enough knowledge to consciously build the representation to the point where it will.

The most interesting contrast in this example is that between person B and person C. They have the knowledge necessary to enable them to ask relevant questions of the materials and thus to improve their understanding of the problem. Person B can do this rather effortlessly by generating questions from the problem representation. Person C, however, must consciously and skillfully elaborate the problem representation before asking questions. To exhibit the same performance, person C has to apply more effort than does person B. Competent performance in this case is a joint function of accessible knowledge and available general cognitive skills.

Rabinowitz and Chi (in press) have made a distinction between *general-context* and *specific-context* strategies that is relevant here. A general-context strategy is one that is exhibited in situations in which a person chooses to use a strategy primarily on the basis of the general constraints of the task. In this situation, the person makes the decision to use the strategy at the start of the task, that is, before the actual materials are viewed. An example of such a strategy, in the case of studying behavior, might be the use of an outlining strategy, such as to glance quickly over the material to get an outline of what might be discussed. The decision to use such a strategy is made prior to looking at the specific nature of the materials. The specific information presented in the passage, or how that information is related to prior knowledge, cannot influence the decision to use the strategy. It seems that the important prerequisite for the use of such a strategy is metacognitive knowledge—knowledge of the general aims of the task and knowledge of which strategies might be applicable.

Alternately, the decision to initiate a specific-context strategy is made in response to a specific, rather than the general, situation. This usually entails noticing similarities, differences, or gaps in knowledge. The decision to use a specific-context strategy is not made at the start of the task. For example, the question-asking strategy studied by Miyake and Norman (1979) can be considered to be a specific-context strategy. Subjects used this strategy only in response to certain specific situations, and the ability to notice these specific situations was based on prior knowl-

edge. Similarly, the working forward and working backward strategies used by experts and novices during physics problem solving were generated in response to accessing specific information form the materials. The ability to access such information was determined by the knowledge that the subject had of the domain. Notice that experts switched to a different strategy when less knowledge of the problem was accessible. Thus, although the exhibition of general-context strategies depends primarily on metacognitive skills, the exhibition of specific-context strategies seems to depend to a large extent on domain-specific knowledge.

Although the decision to use a general-context strategy may be made independently of domain-specific knowledge, the effects of using such a strategy might be to help increase knowledge. For example, the use of the outlining strategy discussed earlier might lead to better acquisition and thus greater knowledge. The ability to use such strategies may be a significant component of giftedness (Campione et al., 1982; Sternberg & Davidson, 1983).

How can such strategies be acquired? One way is for them to be explicitly taught at some time (Palincsar & Brown, 1984). By explicitly teaching such strategies, people's metacognitive knowledge would improve and such strategies would then be applied in a variety of situations. However, general-context strategies can also evolve from specific-context strategies. Through experience with a specific task, a person might come to expect some regularities in the stimulus situation. Thus, strategies that were initially a response to some specific context might come to be employed at the beginning of the task with the expectation that it will, in fact, be a useful strategy. It is also possible that strategies used in several specific contexts become decontextualized so that they might be employed in a variety of tasks. Thus, specific-context strategies could become general-context strategies and subsequently be used to build up knowledge in a variety of domains. In this case the ability to use the strategy initially, the specific-context strategy, was strongly dependent upon knowledge. Thus, the acquisition of general strategies, based on this view, is derivative of domain-specific knowledge.

We have emphasized that knowledge can be a framework for understanding highly competent performance. But how the interactive development and use of general cognitive strategies and knowledge-based processes account for gifted performance is an open question (Glaser, 1984; Glaser, in press; Sternberg, in press). To what extent is outstanding competence dependent upon knowledge structures that rapidly provide relevant information and generate representations? In addition, how is such performance dependent upon skills that enable people to build up and use such knowledge bases? What are the task conditions that differentially call upon these abilities? Clearly, research needs to be conducted on the differences between gifted and average people in the acquisition of knowledge and related cognitive skills, in the accessibility of infor-

mation, in the representations of problem situations, and on how such differences determine the properties of outstanding performance. Such research could contribute a great deal, not only to our understanding of gifted people and to methods of nurturing their talents, but also to educational practices for raising the general level of cognitive competence and intellectual skill.

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